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ABSTRACT

The process of conceptual change, in learners and in scientific knowledge, indicates that: (1) change involves complex and varied commitments to methods of investigation, aims and goals of investigation, and prior knowledge; (2) change leads to consensus forming or dissensus forming activities; (3) knowledge claims and procedures for testing knowledge claims are not held to be equally important by individuals; and (4) anomalous data play an important role in bringing about changes to commitments and fostering either consensus or dissensus forming activities. Historical episodes of the development of theory, method, and aim commitments within a specific scientific domain are the way these four indicators can be incorporated into a science curriculum. The relationship between the intended curriculum and the implemented curriculum is described. A principled reasoning curriculum can be designed using frameworks from the history and philosophy of science that describe knowledge change. (KR)

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Guiding Science Instruction: The Use of Historical Analyses

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Introduction

Among the many new directions advocated for educational reform is the proposal that students examine select areas of knowledge in depth (Linn, 1987). The traditional "overview-of-knowledge" approach within a given domain does not, the critics maintain, provide learners with any sense of how a domain's base of knowledge has come to be the most relevant or important knowledge. The present convention in school science programs is an emphasis on what is known; the facts, principles, laws, theories of science if you will. Such breadth-of-knowledge science curricula coupled with the limited amount of time a teacher is typically allocated to teach a specific topic makes it near impossible to teach strategic or principled knowledge meaningfully. With each new turn in the curriculum, students are compelled to learn a new set of basic concepts. Science becomes an introduction to type of curriculum rather than a thinking about type of curriculum.

The call for the establishment of new curricula that emphasize the development of students' conceptual structures, procedural skills, learning strategies, self-regulatory functions and motivational orientations represents a new conception of aptitude, learning, development and achievement (Snow, 1989; Resnick & Klopfer, 1989). Such a multi-faceted approach to education places diagnosis of instruction and learning at the core of pedagogical and curriculum decision making activities. Fredericksen and Collins (1989) introduce the concept of systemically valid tests for assessment instruments that stimulate both curricular and instructional changes by teachers, and educational systems, that "foster the development of the cognitive skills that the test is designed to measure" (p 27). Their proposal of a systems approach to educational testing is ultimately one that seeks to affect learning strategy changes in students. The purpose of this paper will be to argue that procedural guidelines from history and philosophy of science for evaluating and testing scientific theories and for describing theory restructuring can be used as pedagogical and learning strategy guidelines in science instruction.

Both the research on learning and the research in history and philosophy of science supports the claim that the growth of knowledge is best described by the processes of replacement, modification, and adjustment (Hodson, 1988; Duschl, Hamilton, & Grandy, 1990). Furthermore, close examination of these processes of conceptual change, in learners and in scientific knowledge, indicates:

- 1) change involves complex and varied commitments to methods of investigation, to aims/goals of investigation, and to prior knowledge,

- 2) change leads to either consensus forming or dissensus forming activities,
- 3) knowledge claims and procedures for testing knowledge claims are not held to be equally important by individuals,
- 4) anomolous data play an important role in bring about changes to committments and fostering either consensus or dissensus forming activities.

My thesis is that historical episodes of the development of theory, method, and aim commitments within a specific scientific domain can best incorporate the four indicators above into a science curriculum. First, the development of scientific theories is the goal of scientific inquiry and historical analyses (e.g.; Nersessian, 1987) suggest that developmental steps do exist for the discovery of knowledge. Second, criteria do exist for the evaluation of scientific theories (e.g. Giere, 1988; Root-Bernstein, 1984) and for describing the processes associated with theory restructuring (e.g., Laudan, 1984; Shapere, 1982). Third, the historical analyses of knowledge development and criteria for theory evaluation help to indentify the data that were, or still are, considered to be anomalous data (Duschl, 1988; 1990). Fourth, the developmental steps and evaluative criteria for the generation of scientific theories constitute a set of strategic knowledge guidelines teachers and learners might use in the development of surface as well as deep knowledge claims (Vosniadou & Brewer, 1987).

The problem is complex and although it is impossible to totally divorce the issues of teacher, student, subject matter, and milieu from one another, in this paper my attention shall turn to matters of curriculum and how the other commonplaces of classroom relate to curriculum. The first section of the paper shall introduce the problem of making the intended curriculum the implemented curriculum. I shall then identify a number of charateristics from history and philosophy of science that might serve as generic principles to format science curriculum and instruction. I shall then apply these principles as a first approximation toward the development of a principled knowledge curriculum approach in science education. The adoption of principled criteria from history and philosophy of science is a viable procedure to format a pared down 'Depth of Knowledge' science curriculum.

Making the Implemented Curriculum the Intended Curriculum

An important lesson learned from the first NSF involvement in curriculum development is the various ways in which teachers can change the intended curriculum. Connelley (1972), in a review of science education research, reports that curriculum developers intentions are often lost in the transmission of the curriculum to teachers

and then to students. Roberts (1986) calls it the modulation of the curriculum. Attempts to develop an effective curriculum framework must, Roberts argues, allow teachers to see the developer's intentions embodied in curriculum materials. In order to fully integrate the ideas of cognitive science and epistemology into the teaching and the learning of science it will be necessary for writers to consider how such epistemological and psychological principles can assist in making the intended curriculum the implemented curriculum. It is important to recognize that the harmony Hodson (1988) says exists between psychology and epistemology, exists only in the intended curriculum.

Cognitive views of learning and of teaching place new and challenging demands on teachers. As indicated by the variety of recent research addressing cognitive structures in teacher decision making (Clark & Peterson, 1986) and in learning (Wittrock, 1986) there are, it seems, no fewer than three important information processing steps in a given instructional task involving student, teacher, subject matter.

First, there are the learners' prior conceptions of the knowledge claims that are to be learned. I will call this relationship the **individual-knowledge relationship**. Next there is the **student/teacher-knowledge relationship**. Here the concern is with teacher cognition and teacher decision-making. Cognitive models of teaching and learning, not unlike all models of teaching, require teachers to be cognizant of student learning. The implication is that teachers should be able to evaluate or diagnose students' level(s) of understanding of concepts in an instructional sequence and prescribe restructuring instructional activities as needed. (Wittrock, 1986). Finally there is the relationship between the student and knowledge as that knowledge has been provided by the teacher. Call this the **learner-knowledge relationship** with learner differentiated from student as a result of the active intervention of the instruction formatted and provided by the teacher.

Collectively the three knowledge relationship domains affect how the intended curriculum becomes the implemented curriculum. Conventional views of curriculum (Posner & Rudnisky, 1986) separate the curriculum plan - what is to be learned; from the instructional plan - how to facilitate learning. The position that will be developed here is that epistemological frameworks that seek to explain the justification and development of scientific theories can be affective strategic knowledge guidelines for teacher to use in their decision making and should, therefore, be included in a science curriculum framework.

In order to produce an implemented curriculum that is close to what is expected in the intended curriculum our expectations of teachers' knowledge bases must

necessarily be high.. Shulman (1986) helps us understand the complexity of the problem of teacher knowledge when he suggests that three types of knowledge are fundamental to the preparation of quality teachers - 1) content knowledge, 2) pedagogical knowledge, and 3) curriculum knowledge. It will be the goal of the present paper to establish that epistemological frameworks of the content knowledge domain can provide teachers with decision making strategies that inform them about shaping both pedagogical knowledge and curriculum knowledge in ways that enhance students capabilities to reason scientifically. More exactly, the inclusion of frameworks about the growth of scientific knowledge provide teachers with strategic knowledge guidelines to assist them in decisions about both what to teach and how to sequence the instruction.

Among the many contributions cognitive psychology have made to science education, one in particular is relevant to the present discussion. It is the discovery that expert knowers employ two sets of knowledge. One is a declarative or domain specific knowledge component and the other is a procedural or strategic knowledge component. The importance of this division of knowledge for curriculum writers is the strong evidence (Alexander & Judy, 1988) that students use of strategic knowledge frameworks contributes positively to their academic gains.

The challenge, then, for curriculum writers is how best to integrate both the declarative knowledge structures and the procedural knowledge structures of a discipline into the framework of curriculums. If the use of strategic knowledge is relevant for learners, then, I submit, it is equally, if not more, important for teachers. To design a curriculum framework that negates teacher input and modification at the level of classroom instruction is to ignore the lessons of the past (Roberts, 1980/1986). The implication is teachers need to expand their content knowledge and instructional decision making to include both declarative and procedural components of the growth of scientific knowledge. Knowledge about science as portrayed by historians and philosophers of science is, I maintain, as necessary component of teacher knowledge.

New Views in Philosophy of Science

The work of historians and philosophers of science has helped to advance the position that the growth of knowledge in science is best understood as a series of changes to scientists' fundamental explanations of how and why things work. From the analysis of the work of historians of science, philosophers of science discovered three things were indicated about the nature of science (Shapere, 1984):

- 1) that standards used for assessing the adequacy of scientific theories and explanations can change from one generation of scientists to another;
- 2) that the standards used to judge theories at one time are not better or more correct than standards from other time period; and
- 3) that the standards used to assess scientific explanations are closely linked to the beliefs of the scientific community from that time period.

Thus, contemporary studies on the nature of scientific inquiry focus on how theories of science come to be, how theories proceed through stages of development, and how theories are replaced.

The upshot of all this for science educators is that it is now possible to speak about science knowledge in terms of its context of development. The importance of this developmental perspective to science education is the processes of acquiring scientific knowledge are quite similar to guidelines employed in the processes of learning. Hodson(1988) proposes that the view of science which arises from the work of historians and philosophers of science have generated concepts of science which are quite similar to newer views cognitive scientists propose for how children learn science. Simply stated both the processes of learning by students and the growth of knowledge in the field of science are considered to involve mechanisms in which new ideas replace old ideas. Although there are tensions to this analogy (Duschl, Hamilton, & Grandy, 1990), it is nonetheless quite worthy of pursuit.

Prior to the 1950s, the nature of science was understood through the analysis of only the most highly developed of the sciences - physics and chemistry - and the examination of the fully developed mathematical theories of science (Shapere, 1986). The examination of such deterministic explanations, i.e., Newton's Laws of Motion, established a view of science which made understanding the testing of knowledge claims much more important than understanding how knowledge was discovered and restructured. It was unimportant to try and understand how ideas were first conceived and how they evolved over time.

Philosophical considerations of knowledge growth in other disciplines (i.e., geology and biology) or domains of science, however, have indicated that fundamentally different sets of criteria are employed by scientists within different disciplines (Laudan, 1977; 1984; Giere, 1988; Suppe, 1989.). The goal of science is always the same - the development of explanations that provide an understanding of the nature of the world - but different guiding conceptions give rise to different methods used to obtain explanations and to solve problems. Basically, when we examine the nature of scientific inquiry as it is practiced we find that this scientific inquiry just isn't as neat

and clean as we often propose. Rather, it is in a continual state of flux in which theories, methods, research questions and the sort compete for supremacy. But this is not to say it is totally devoid of standards or frameworks for judging competing ideas and making choices among them. No, it merely establishes that there is a great deal more which needs to be taken into consideration and a great deal more which ought to be embodied in the curriculum planning and decision making frameworks of our science classes.

Thus the relations between observation and theory and between the testing and development of knowledge claims became two of the more important issues in philosophy of science in the 1950s and 1960s and are represented by the following questions:

- Was it possible to have observations free of theory?
- Did commitments to theory affect measurement and interpretation of data?
- How did scientists' develop theories?
- Is there a single preferred form for theories?
- Is the development or alteration of theoretical ideas rationally constructed?

What the critical histories of science discovered was that the growth of scientific knowledge wasn't an activity which grew without disruption, upheaval or alteration to central ideas. Historians of science national studies, discipline studies, science and religion studies, science, medicine, and technology studies, philosophy, psychology, and sociology of science studies, and great people studies have had a significant impact on the discourse in philosophy of science. These historically grounded studies provided new developmental perspectives for philosophers of science. The new methods for writing history of science and the new findings from such analyses provided historians and philosophers of science with evidence that the rigid form of science advocated by logical empiricists and logical positivists just did not exist. Rather, what is revealed by these histories of science is that all aspects of science; its standards, meanings of terms, application of methods, and theoretical forms, are restructured (Thackray, 1984; Shapere, 1989; Laudan, 1984; Suppe, 1989). What emerges is the centrally important role of theories in science. (See Appendix A for a list of titles in history of science relevant to science education.)

Scientific Theories and Strategic Knowledge

Understanding how theories develop and how theories affect other aspects of science can provide science teachers with a very powerful set of strategic knowledge guidelines useful in their curriculum and instructional decision making. Some of the general guidelines significant to science teachers include: ,

- 1) all scientific explanations are not equal, some ideas are more important than other ideas,
- 2) a scientific explanation can rise and fall from grace in the scientific community,
- 3) criteria do exist for judging or evaluating scientific explanations.
- 4) a description of the rational evolution of scientific explanations is possible.

The analyses made by historians, philosophers, and sociologists of science on the changes which occur in scientific knowledge make it quite clear that an understanding of the growth of scientific knowledge is best obtained through an understanding of the development of scientific theories. Thus, a better understanding of scientific reasoning and of the factors which contribute to the growth of scientific knowledge can be acquired through considerations for the structure of scientific theories.

There is a need then to embody in our science curriculums strategic knowledge guidelines that assist teachers and learners in the assessment of both historically relevant and extant knowledge, method, and aim commitments held by scientists. Although instructional frameworks that solicit students explanations, views, and representations of concepts and instructional tasks do exist (e.g., the focus/clarification stage of the generative learning model [Osborne & Freyberg, 1985] and the elaboration stage of the learning cycle [Champagne, 1988]) these frameworks lack specific strategic knowledge guidelines that assist learners and teachers in the difficult task of judging or assessing the status of the knowledge claim. For purposes of this discussion, I want to restrict my use of knowledge claims to explanatory statements and those concepts germane to the explanatory statement. My thesis is criteria used to evaluate the status of scientific theories, which are explanatory statements, and to describe the dynamics of theory restructuring, including abandonment of a theory, can serve as useful strategic knowledge guidelines for teachers. It will be argued that select epistemological frameworks of science employed with historical cases can serve as principled knowledge in science classroom.

Principled Knowledge in Science Classrooms

The research on conceptual change strategies (Gunston, White & Fensham, 1988) suggests that learners explanations and meanings of concepts are very resilient. Chi (1990), Vosniadou & Brewer (1987), and Duschl, Hamilton, and Grandy (Forthcoming) each follow the lead of Carey (1985) in suggesting that there are two types of conceptual change - weak restructuring of concepts within a domain and radical restructuring of concepts to form new domains. Strike and Posner (Forthcoming)

and Chi (Forthcoming) compare the radical type of change to shifts across paradigmatic boundaries. The research suggests that the cause for the resistance to change is explain by the complexity of the process which is radical in nature.

Among the researchers cited above there is agreement that considerations for the historical development of explanations and theories can provide assistance. Chi (1990) has found, for example, that children hold material substance views of physical science concepts (i.e., heat, current,) that are not material substances. Nersessian and Resnick (1988) argue that the material substance views of these physical science concepts held by novice learners is consistent with the theories held by medieval scientists. Historical analyses, then, of how theory restructuring occurred can serve as a basis for instructional design and as a model for understanding conceptual change.

I have argued (Duschl, 1990; 1988) that a theory of conceptual change or knowledge restructuring based solely on knowledge structures is inadequate. Employing the epistemological frameworks of Root-Berstein (1985) to evaluate theories and Laudan (1984) to describe theory change it is possible, I contend via a reasoned argument, to format instruction which can facilitate radical conceptual change among learners. Several assumptions, however, are made about the instructional environment. First, a depth of coverage curriculum approach is assumed. Second, teacher knowledge is grounded in both what is known in science and how it came to be known. Third, the classroom environment supports a learning environment in which principled/strategic knowledge guidelines are an implicit component of student and teacher activities. The remainder of the paper will elaborate on the last of these three assumptions.

Research in mathematics education carried out by Resnick (1989; 1988; 1986), Greeno (1988), Lampert (1986) and Leinhardt & Smith (1985) has pointed out the importance of linking cognitive skills to the disposition to use them. The goal is to get students activity employing rather than just stating the rule/principles/strategies of mathematics. One approach to the problem of getting students to use strategies is the employment of principled knowledge teaching techniques (Lampert, 1986; Resnick, 1989). The focus of instruction is to have students implicitly use sophisticated mathematical principles in the solution of authentic tasks familiar to students. For example, Lampert (1986) has students solving coin problems, three-digit addition problems and multiplication problems, that require students to use the associative, communicative, and distributive laws of numbers. Students take steps in the solution of math problems that use the principles of math and all the while students are learning implicitly a principled way of knowing mathematics. Resnick (1989) has had similar

success with a school based mathematics research project that seeks to develop in primary grade students the disposition to use critical thought. Her position is:

"shaping a disposition to critical thought is as important in developing higher order cognitive abilities in students as is teaching particular skills of reasoning and thinking. This, in turn, requires an educational program that is suffused with thinking and reasoning, one in which basic subject matter instruction becomes the daily occasion for exercising and extending these cognitive abilities." (Resnick, 1898; p. 1).

Hence, the task of instruction requires students to actively engage in the reasoning to solutions employing select elaboration and scaffolding techniques introduced by the teacher. Basic to these approaches is creating a learning environment in which the process to a solution is valued more than the correct solution to a problem. Thus, students are encourage to record multiple solutions to Lampert's (1986) coin problem - "Using only two kinds of coins, make \$1.00 with 19 coins." and solve multiplication problems using different strategies. Similarly, Resnick (1988) reports problem solving success with children using planning boards. This scaffolding technique, like Lampert's technique, enlists students to consider multiple perspectives. In the case of the planning board, students list "What We Know" and "What We Need to Know" statements in separate columns.

A critical element in the success of these teaching episodes is the background knowledge of the teacher. In the case of the Lampert research, for example, she is doing the actual teaching and has a clearly stated sequence of instructional activities that implicitly engage students in reasoning with the principles of mathematics. Can a similar approach be taken in science education? My answer is yes and the strategic or principled guidelines come from evaluative criteria for evaluating theories and describing the development of scientific theories. (I realize I am taking some liberties applying the use of principled knowledge to science and can be criticized by those who contend that science while it does contain procedures and strategies does not contain principles of problem solving like those in mathematics. But with a relax criteria for what counts as principled knowledge I think the argument holds and the development of a disposition to reason scientifically can be fostered among learners.)

Applying Philosophical Analysis to Practice

The application of philosophical analysis to examine practice in science education is a standing research tradition (Roberts & Russell, 1975). A specific case in which philosophical considerations were used is Russell's (1983) employment of Toulmin's

(1958) argument pattern to analyze teachers' science classroom discourse (See Figure 1). The study examined the extent to which teachers' authority of knowledge was either irrationally based (i.e., appeal to teacher knowledge as reasons to accept scientific knowledge claims) or rationally based (i.e., appeal to scientific warrants and background knowledge as reasons to accept scientific knowledge claims). Toulmin's argument pattern provided Russell with an effective clue structure for the analysis of teachers discourse. His results suggest that teachers who require from students and themselves warrants to reason from data to conclusions are perceived as rational authority figures. It is easy to see how this argument pattern could be adapted to create a principled knowledge learning environment in which all statements of conclusion from textbooks, films, students lab reports, teacher lectures would require warrants and backings to justify the move from data to conclusions. Learners are amenable to the practice of requiring evidence for the support or refutation of arguments. What makes the practice somewhat more difficult in science is that what counts as evidence or as an exemplar of a scientific principle is remote to the experiences of the learner.

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Another example of applying philosophical analysis to practice is Gowin's Vee heuristic (Novak & Gowin, 1984). Here students are guided during the doing of science to connect investigative results with the epistemological frameworks of scientific knowledge claims. The emphasis is on the development of metacognitive strategies in learners. My (1990) presents four different epistemological models that can be employed by teachers and curriculum writers to format instruction. Two of the models focus on the testing of scientific theories and two address the development of theories. The first of the testing models is an argument pattern for testing theories (See Figure 2.) (Giere, 1984) and the second is a set of 4 criteria to be used in the evaluation of theories (See Table 2)(Root-Bernstein, 1984) The two models for describing theory restructuring are taken from Laudan (1984) and Shapere(1981). Collectively, the four frameworks provide procedural guidelines teachers can employ to create a principled learning environment that seeks to create in students a disposition toward critical thinking.

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The above assertion is based on the teaching and research I have performed as part the 'Foundations of Science' courses offered at Hunter College-CUNY. Students in the course study the historical development of knowledge claims central to three story lines. Framed as questions the story lines are:

- 1) How did we come to reason that the Sun is the center of the solar system and that the motion of planets is governed by the force of gravity?
- 2) How have we come to reason that matter is particulate?
- 3) How have we come to reason that the Earth and life on Earth have an elaborate history?

Through a series of readings, lectures, labs and essay writing assignments students would explore the development of knowledge claims that contribute to our present day understanding of a scientific view of the universe. Thus, students would be introduced to a series of theoretical models with instruction emphasizing the reasoned arguments for favoring one explanatory model of nature over another (i.e., equal area motion of planets over uniform motion of planets; molecular structure models of compound formation over Berzelius' electrochemical theory; Hutton's Plutonist view of rock formation over Werner's Neptunist View) As a lab instructor in the course I was responsible for reading and commenting on students essays and, of course, was the first to learn of the confusions that students had in learning the science concepts. The confusions were many (Duschl, 1989).

Through the teacher/student lab interactions and the research interviews I conducted with students during my two year involvement with the course I found that students inability to separate statements into meaningful categories inhibited their ability to reason. Statements of different kind are treated as equally important to the resolution of a problem or the understanding of an argument.. I found there was very little differentiation among statements of evidence, statements of methods, statements of research aims, or statements describing existing models by students. What seemed to be lacking was a strategic knowledge framework that would assist learners in reasoning why one model was or wasn't a better explanation of a physical or biological system than another. A critical problem here was the inability of students to recognize anomalous data as that, anomalous data. The historical path of knowledge growth includes any number of instances when new methods provide new ways of conducting observations, when these new ways of seeing generate new sets of data, and these new sets of data give rise to new reasoned arguments. It is a dual reasoning that takes place, however, because at each instance when a new model emerges it does so at the expense of an existing model.

### Consensus and Dissensus in Conceptual Change

In order to tell the historical story accurately, both consensus forming and dissensus forming developments of science need to be reflected in the curriculum. When changes in science are described in broad details - once we believed the Earth was at the center of the universe but now we believe the Earth revolves around the Sun- students are too often left with the impression that changes in scientific knowledge come about quickly, holistically, and at time irrationally to a community of scientists. Laudan (1984) is helpful here.

Laudan(1984) argues that hierarchical models of holistic conceptual change like those put forth by Kuhn (1970) and Lakatos(1970) put too much emphasis on the affect changes in theoretical commitments have on changing methodological commitments and investigative aim commitments of scientists. Such a view of change to scientific theory is faulty for several reasons according to Laudan (1984). First, holistic change models inaccurately describe how scientific consensus and dissensus take place. Laudan argues that change in science is less holistic and more piecemeal is character. For Laudan, the notion of change is one in which changes to scientific theories, methods, and aims can and do occur separately and within distinct and mutually exclusive periods of time. Thus, although there might be a change in theory commitment there need be no instantaneous change in commitments to methods or aims. Laudan refers to this type of change as piecemeal change and, as is demonstrated in the case of the Hunter College course, it can be reflected in historical cases of the development of scientific knowledge.

A second important distinction Laudan makes between piecemeal and holistic models of scientific change is the emphasis placed on the role of consensus activities in science. On those occasions when enough anomalous data has accumulated to provide evidence that a change in science is needed, these are times when dissensus activities among scientists dominate. Hierarchical models of change tend to smooth over this important replacement and substitution component of scientific change. Dissensus considerations are important not only because it more accurately describes the process of change in science but also because studies (Gunstone, White, Fensham, 1988) show that in learners do not easily adopt new explanations.

A third distinction Laudan makes is between the piecemeal and holistic models of scientific change is that the latter frequently overlooks the important role aims and methodology have in establishing the anomalous evidence which brings about conceptual change. We must ask, therefore, what activities in science spawn anomalous data. Certainly one dominant source of new data is the adoption of new technological devices by

scientists. These new devices affect the methods scientists employ. Consider the impact the microscope, telescope, seismograph, x-ray tube, or computer, we could go on and on here, have had on the form of data scientists have at their disposal. Laudan's piecemeal approach focuses our attention on the important role the tools, cognitive strategies and technologies used by scientists have on bringing about dissensus activities and, thus, eventuating change in science.

In a similar vein, changes with the aims of scientific inquiry can also provide the impetus needed for spawning new sets of anomalous data. The investigative methods of science determine how we look. The investigative aims of science determine where we look. Consequently, when considering influences on aims we must recognize the important role social factors have on the activities of scientists and scientific institutions. World War II had an enormous affect on the rate at which new technologies were developed; technologies which eventually gave rise to new models of the ocean floor and geodynamics. Our space program is an example of how a scientific institution with political and financial support can produce theory-altering sets of data. Clearly, our knowledge of the planet Earth today, a knowledge forged from data collected by various satellites, is significantly different than the knowledge of the Earth we had prior to 1960. One significant example is hurricane tracking and warning.

### Summary

I have argued that epistemological frameworks that describe theory restructuring and that provide criteria to evaluate theories can be used as strategic knowledge guidelines in science education. A problem in science education is the differences that exist between the intended curriculum and the learned curriculum. The intermediate step in this curriculum continuum is the translated or implemented curriculum. Cases from history of science and frameworks from philosophy of science can be adopted as strategic knowledge guidelines upon which instructional practice and pedagogical decision making can be based.. It is my contention that the adoption of such frameworks will prove valuable in addressing differences between the intended and learned curriculums.

The process of knowledge growth is not governed exclusively by commitments to theories. There are three levels of commitment scientists' employ:

- 1) theoretical commitments,
- 2) methodological commitments, and,
- 3) goal of science or aim commitments.

Consideration for these three levels of commitment can, I maintain, be a useful set of strategic knowledge guidelines to foster conceptual change when 1) used in combination with other theory testing guidelines and 2) taught within the context of a historical case. Taken together, they have the potential to provide science teachers with the procedural guidelines to implement a principled learning environment and, in turn, a reasoning curriculum in science.

I have argued elsewhere (Duschl, 1988) that a failure to affect changes in students' conceptions can be attributed to instructional models that place too much emphasis on theory commitments in learners and not enough emphasis on method and aim commitments. Research on conceptual change learning (Chi, 1990; Strike and Posner, In Press) has begun to question the role of anomalous data in affecting change. It remains to be established, however, what it is that counts as anomalous evidence to learners. It also isn't clear if it is a learning problem associated with learner's cognitive constraints or a teaching problem associated with poor instructional practices.

My paper has focused on the latter of these two issues. I maintain a principled reasoning curriculum can be designed using frameworks from the history and philosophy of science that describe knowledge change. The power of the principled reasoning curriculum is that it not only provides strategic knowledge guidelines for learners but, and perhaps more importantly, it provides strategic knowledge guidelines for the teacher. Such guidelines I contend would assist in making the intended, translated/implemented, and ultimately learned curriculum more consistent.

As with the math curriculum, science teachers can implicitly at first and explicitly later on provide students with a rich array of strategic knowledge frameworks. The argument pattern of Giere can be used like Russell's use of Toulmin's argument pattern to guide teacher/student discourse. The criteria proposed by Root-Bernstein elaborate on the reasons for judging between theory statements. Laudan's Triadic Network reminds us of the importance of scientists' commitments to more than theory. Aim commitments and method commitments are equally important to consider in the analysis of knowledge growth in science. These frameworks and the of Tripartite Observation scheme of Shapere's can, in turn, serve as bases to evaluate knowledge claims and scientific data that don't fit with prevailing conventions; be they those of the student or those of a community of scientists. In time, students will come to understand the degree of legitimate doubt that can be attached to a scientific knowledge claim.

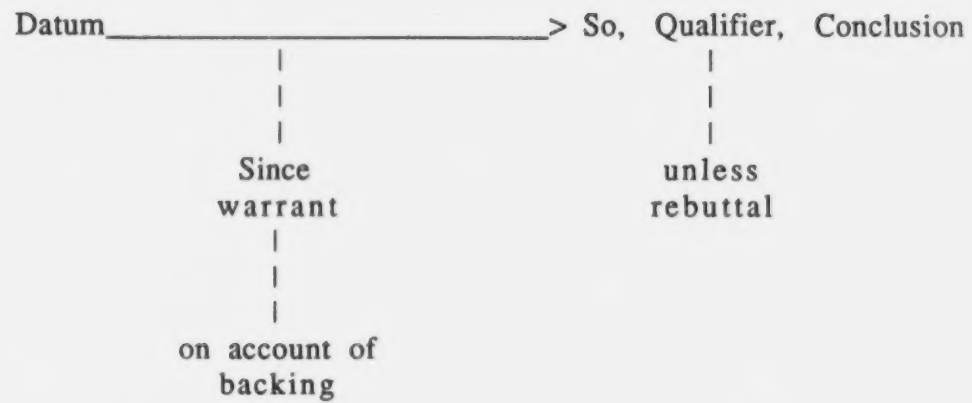


Figure 1. Toulmin's Argument Pattern

H -

The continents on the surface of the Earth were once joined together as a single land mass.

IC -

1) The continents on the opposite shores of the Atlantic can be pieced together like a puzzle.

2) Glacial deposits and plant fossils of the same age are found on the continents of S. America, Africa, Australia, and Antarctica.

3) There isn't enough water on the planet to make a glacier large enough to extend to these continents given their present positions; nor could the fossils which are found in the rocks transport themselves across the oceans.

4) Geological structures, i.e., faults and rock types, of the same age and with similar lithologies and orientations can be found on N. and S. America and on Africa.

B -

Physical theories hold that the earth is a solid object.

P -

The continents on the surface of the Earth are moving with respect to one another or drifting.

Figure 2 - Giere's (1986) Argument Pattern for Testing Scientific Theories.

H - Theoretical Hypothesis; IC - Initial Conditions; B - Background Knowledge; P - Prediction. The example used here is an argument for the rejection of the Alfred Wegener's Theory of Continental Drift.

**Table 1**  
**Four Criteria for Evaluating Scientific Theories**

**Logical Criteria** - (Root-Bernstein, 1984; p 65):

- 1a - It must be a simple, unifying idea that postulates nothing unnecessary ("Occam's Razor");
- 1b - It must be logically consistent internally;
- 1c - It must be logically falsifiable (i.e., cases must exist in which the theory could be imagined to be invalid);
- 1d - It must be clearly limited to explicitly state boundary conditions so that it is clear whether or not any particular data are or are not relevant to the verification or falsification of the theory.

**Empirical Criteria** - The four criteria state (p 66):

- 2a - A theory must be empirically testable itself or lead to predictions or retrodictions that are testable;
- 2b - A theory must actually make verified predictions and or retrodictions;
- 2c - A theory must concern reproducible results;
- 2d - A theory must provide criteria for the interpretation of data as facts, artifacts, anomalies, or as irrelevant.

**Sociological Criteria** - A theory must (p 67):

- 3a - resolve recognized problems, paradoxes, and/or anomalies irresolvable on the basis of preexisting scientific theories;
- 3b - pose a new set of scientific problems upon which scientists may work;
- 3c - posit a "paradigm" or problem-solving model by which these new problems may be expected to be resolved;
- 3d - provide definitions of concepts or operations beneficial to the problem-solving abilities of other scientists.

**Historical Criteria** - The three historical criteria state that a theory must (p 67-68):

4a - meet or surpass all of the criteria set by its predecessors or demonstrate that any abandoned criteria are artifactual;

4b - be able to accrue the epistemological status acquired by previous theories through their history of testing - or, put another way, be able to explain all of the data gathered under previous relevant theories in terms either of facts or artifact ( no anomalies allowed);

4c - be consistent with all preexisting ancillary theories that already have established scientific validity.

## Appendix 1

The following books are recommended as an introduction to topics in the emerging field of history of science:

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